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SN 1987A Gamma-Ray Limits on the Conversion of Pseudoscalars

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Abstract

Pseudoscalar particles ϕ usually couple electromagnetically by an interaction of the form $\frac{1}{4}g\phi F\widetilde{F}$, allowing them to convert to photons in the presence of magnetic fields. Notably, new low-mass pseudoscalars emitted from supernova (SN) 1987A would have been converted to γ-rays in the intervening magnetic field of the galaxy. Therefore, measurements by the Solar Maximum Mission (SMM) Gamma-Ray Spectrometer (GRS) can limit the inverse coupling constant to $g^{-1} > 1\times 10^{11}\,\mathrm{GeV}$, assuming the pseudoscalar is massless. This is an improvement over other astrophysical limits of a factor of about 2.5.

I. INTRODUCTION

Light neutral pseudoscalars arise naturally as a result of spontaneously broken global symmetries [1]. They will be truly massless if the symmetry is not anomalous. Such particles generically couple to the electromagnetic field through an interaction of the form

$$\mathcal{L} = \tfrac{1}{4} g \phi F^{\mu\nu} \widetilde{F}_{\mu\nu} \,, \tag{1}$$

where $\widetilde{F}_{\mu\nu}$ is the dual of the electromagnetic field-strength tensor $F^{\mu\nu}$ and g is a coupling constant of dimension (energy)$^{-1}$ which is related to the scale of symmetry breaking. This coupling leads to the interconversion of photons and pseudoscalars in external electric or magnetic fields. Just as the pion decay constant was originally measured by this Primakoff effect, it is natural to investigate the existence of new pseudoscalars by this method. For example, two beautiful experiments to search for the presence of dark-matter axions in our galaxy are currently under way [2].

If new low-mass bosons exist, stars will be powerful sources for their production [3,4]. Therefore, a classic way to constrain the coupling g is from observational limits on anomalous stellar energy losses. The observed helium-burning lifetime of horizontal-branch stars yields a limit $g^{-1} \gtrsim 1.7\times10^{10}\,\mathrm{GeV}$, applicable if the particle mass is not much larger than the stellar core temperature of about 10 keV and thus covers the important case of axions [4,5].

However, if the pseudoscalar mass is very small, more restrictive limits can be obtained from the possible conversion of stellar particle fluxes in the large-scale magnetic field of the galaxy. This effect would lead to apparent x-ray or γ-ray fluxes from stars since the emitted pseudoscalars have energies representative of the interior temperature. Essentially, then, one would observe photons from the stellar core which were converted there to pseudoscalars in the electric fields of the charged particles of the heat bath, and which were then back-converted into photons by the galactic magnetic field. One of us (E.C.) has previously applied this argument to the red supergiant α-Ori (Betelgeuse) and found a limit $g^{-1} > 4\times10^{10}\,\mathrm{GeV}$ [6]. Later, one of us (G.R.) pointed out that this method could also be applied to the pseudoscalar flux from supernova (SN) 1987A [4]. The Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) satellite

has set very restrictive limits on a possible γ-ray burst in conjunction with the observed SN 1987A neutrino signal, a fact which has been used to derive limits on neutrino radiative decays [7]. We presently show that these observations yield a constraint $g^{-1} > 1\times10^{11}$ GeV, more restrictive than all previous bounds. Of course, it will apply only to massless pseudoscalars (true Goldstone bosons) and thus excludes axions for which the horizontal-branch star limit remains the most restrictive.

In Section 2 we discuss the theory of pseudoscalar production in the supernova's interior. In Section 3 we discuss their conversion to photons in the presence of the galaxy's magnetic field and the limit which such conversion can achieve. Observational limits on converted photons by the Solar Maximum Mission satellite is discussed in Section 4. We summarize our findings in Section 5.

II. SUPERNOVA PRODUCTION OF PSEUDOSCALARS

Pseudoscalars with a coupling of the form (1) are produced primarily by the Primakoff process. In vacuum, its cross section is logarithmically infinite due to the infinite range of the Coulomb potential. In a medium, however, Debye screening cuts off this divergence and leads to a conversion rate per unit time for photons to pseudoscalars of [8]

$$\Gamma = \frac{g^2\kappa^2 T}{32\pi}\left[\left(1+\frac{\kappa^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{\kappa^2}\right)-1\right], \tag{2}$$

where E is the photon energy, T the temperature, and κ the inverse Debye screening length. The overall factor of κ^2 in this equation is simply a convenient way of writing the density of scattering targets, and has nothing especially to do with Debye screening. The other appearances of κ^2 arise from the finite range of the electric field surrounding charged particles in the plasma.

In order to derive an expression for κ which is appropriate for the conditions of a SN core, we note that the relevant charged particles are equal number densities of electrons and protons. However, because of their large mass difference the electrons are very degenerate, while the protons are nearly nondegenerate, or at most partially degenerate. Therefore, electrons are essentially unavailable as scattering targets because their phase space is almost completely Pauli blocked. Further, their degeneracy causes them to form a "stiff" background which is difficult to polarize

so that they can be ignored for screening as well. Because of the large temperature, the plasma coupling parameter for the protons is much smaller than unity in spite of the large density so that the plasma is weakly coupled in the electromagnetic sense. Therefore, κ is given by the Debye formula

$$\kappa^2 = \frac{4\pi\alpha}{T} n_p \; , \tag{3}$$

where n_p is the number density of the protons and α is the fine-structure constant.

Multiplying Eq. (2) with the density of thermal photons, we find the pseudoscalar volume production rate $\dot{n}_\phi$ per unit energy to be

$$\frac{d\dot{n}_\phi}{dE} = \frac{g^2 \xi^2 T^3}{8\pi^3 (e^{E/T} - 1)} \left[(E^2 + \xi^2 T^2) \ln(1 + E^2/\xi^2 T^2) - E^2 \right] \; , \tag{4}$$

where $\xi^2 \equiv \kappa^2/4T^2$. We stress that it is possible to treat photons essentially as massless particles because the plasma frequency for the conditions at hand is small compared with the temperature.

In order to calculate the total expected flux we use the numerical SN model S2BH_0 of Keil, Janka, and Raffelt [9] which is a representative case. We had numerical details at hand for $t = 1$, 5, and 10 seconds after core bounce. The values of T and ξ^2 as a function of radius are plotted in Fig. 1. Further, in Fig. 2 we show $T/E_{\rm F}$, where the nonrelativistic proton Fermi energy is given by $E_{\rm F} = p_{\rm F}^2/2m_N$. (The Fermi momentum is related to the proton density by $n_p = p_{\rm F}^3/3\pi^2$.) Degeneracy effects typically become truly important only for $E_{\rm F}/T \gtrsim 3$ so that our approximation of treating protons as nondegenerate is quite reasonable.

We then integrate over the volume of the star to get the total rate $d\dot{N}_\phi/dE$ at which particles are produced. It is graphed in Fig. 3 for a coupling strength of $g^{-1} = 10^{10}\,\mathrm{GeV}$. For the earliest time, $t = 1\,\mathrm{sec}$, we may be slightly overestimating the production because of the proton degeneracy.

Once the pseudoscalars are produced, they will escape the supernova provided their mean free path λ for backconversion exceeds the size of the SN core. The backconversion rate is just twice the rate given in Eq. (2). Typical photon and pseudoscalar energies will be around $E = 3T$, so that typically $E/2\kappa = 3/\xi$. In this range the square bracket in Eq. (2) is of order unity. Therefore, $\lambda^{-1} \approx g^2\kappa^2 T/16\pi$, almost independently of the energy. If we use $T = 30\,\mathrm{MeV}$ and $\kappa = 50\,\mathrm{MeV}$ as

characteristic values, we find $\lambda \approx g_{10}^{-2}\,10^{12}\,\mathrm{cm}$ where $g_{10}^{-1} \equiv g^{-1}/10^{10}\,\mathrm{GeV}$. Therefore, in the range of coupling constants which is of interest here, the pseudoscalars escape freely from the SN core once produced.

III. CONVERSION IN THE GALACTIC MAGNETIC FIELD

Having produced our pseudoscalars, we now wish to detect them. To do so, we will back-convert them in the galactic magnetic field. In a field which is roughly homogeneous on scales much larger than the pseudoscalar wavelength, this conversion process can be viewed as an oscillation phenomenon much like that of neutrino oscillations [10]. However, oscillation phenomena will manifest themselves only if the momentum transfer $(m_\phi^2 - m_\gamma^2)/2E$ which is needed to convert a pseudoscalar into a photon exceeds the inverse scale over which the B-field is roughly homogeneous. For photons, the "mass" is given by the plasma frequency $m_\gamma^2 = 4\pi\alpha n_e/m_e$ where n_e of order $0.03\,\mathrm{cm}^{-3}$ is the interstellar electron density. It corresponds to $m_\gamma = 0.6{\times}10^{-11}\,\mathrm{eV}$ or, with a photon energy $E = 100\,\mathrm{MeV}$, to $m_\gamma^2/2E = 2{\times}10^{-31}\,\mathrm{eV} = (30\,\mathrm{Mpc})^{-1}$. The relevant spatial extent of the magnetic field will turn out to be of order 1 kpc so that photons can be viewed as massless for the present purposes in spite of the plasma effect. Similarly, for the pseudoscalars to count as effectively massless we need to require $(m_\phi^2/2E)^{-1} \gtrsim 1\,\mathrm{kpc}$ or $m_\phi \lesssim 10^{-9}\,\mathrm{eV}$.

If photons and pseudoscalars are effectively massless in this sense, the conversion probability is given by

$$P = \tfrac{1}{4} g^2 B_\perp^2 \ell^2 \ , \tag{5}$$

where $B_\perp$ is the magnetic field perpendicular to the line of sight, and ℓ is the distance over which the magnetic field is effectively constant.

The magnetic field of the galaxy has considerable structure. There is certainly a toroidal component with a magnitude of about $2\,\mu\mathrm{G}$ and a coherence length of about 1 kpc. There are also other components, which may be roughly characterized as a random contribution of magnitude $5\,\mu\mathrm{G}$ with a coherence length of perhaps 10 pc. Because the random component cannot contribute

coherently, we anticipate that the toroidal field will be the dominant contribution. Hence we will assume that there is a constant field of $2\,\mu$G. Since 1 kpc is also the approximate thickness of the disk where we expect this galactic magnetic field, we will assume a constant field on this scale, which cuts off suddenly after a distance of 1 kpc. There may also be extragalactic fields between us and the Large Magellanic Cloud; if so, they will only increase the effect. Obviously, there is considerable uncertainty in this calculation, and hence our final result can not be taken as precise.

SN 1987A is at a galactic latitude $b = -32.1^\circ$ and longitude $l = 279.6^\circ$. This unfortunately means that we are looking primarily along the direction of the magnetic field, so that

$$P = \tfrac{1}{4} g^2 B^2 \ell^2 (1 - \cos^2 b \sin^2 l) = \tfrac{1}{4}\, 0.30\, g^2 B^2 \ell^2 \ . \tag{6}$$

The photon flux at Earth is then given by

$$\frac{d\Phi}{dE} = \frac{d\dot{N}_\phi}{dE} \frac{g^2 B_\perp^2 \ell^2}{4\pi D^2} \ , \tag{7}$$

where $\ell = 1$ kpc is the length of the conversion region, $D = 50$ kpc is the distance to SN 1987A, and $B_\perp^2 = 0.30\,(2\,\mu\mathrm{G})^2$. For a coupling $g^{-1} = 10^{10}$GeV, this yields the fluxes plotted in Fig. 3.

IV. DETECTION OF GAMMA-RAYS

Not surprisingly, no detector was oriented specifically in the direction of SN 1987A at the time of core collapse. Fortunately, the Gamma Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM) satellite, though pointed in the direction of the Sun, was still able to detect gamma rays coming from the direction of SN 1987A [11]. The precise timing of the core collapse is known from the observation of neutrinos by the Irvine-Michigan-Brookhaven [12] and Kamiokande II [13] detectors. Because electron neutrinos and photons are both effectively massless they should arrive simultaneously at Earth. Thus we know exactly which period to search for an excess of photons from SN 1987A.

During the 10.24 seconds that the neutrinos were detected from SN 1987A, the GRS searched for photons in three energy bins, 4.1–6.4 MeV, 10–25 MeV, and 25–100 MeV. The 95% confidence limits on the total fluence of photons during this time period were 0.9, 0.4, and 0.6 $\gamma\,\mathrm{cm}^{-2}$ respectively

[11]. Because of the rising shape of our spectrum, the best limit for us comes from considering the highest of these bins. The detailed limit depends on the shape of the spectrum, and the limit cited in [11] assumes a spectrum which falls as E^{-2}. Without knowing more about the energy dependence of the detector's response, we cannot get a precise limit, but we will assume that the limit $0.6\ \gamma\,\mathrm{cm}^{-2}$ applies.

In the highest energy bin, the γ-ray flux from SN 1987A can be found by integrating the rates plotted in Fig. 3. For a coupling of $g^{-1} = 10^{10}$GeV, this turns out to be 2880, 2120, and $1180\,\gamma\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, at $t = 1$, 5, and 10 seconds, respectively. Recall that at $t = 1$ second, there should be a noticeable reduction of the rate from that calculated due to Pauli blocking of the final-state protons. We expect this blocking to be even larger at earlier times, so we ignore all contributions from $t < 1$ second, and assume that our calculations are accurate over the rest of the time period. A linear fit gives a fluence (time-integrated flux) of $1.8{\times}10^4\,\gamma\,\mathrm{cm}^{-2}$ for the period from $t = 1$ to 10 seconds.

Nominally, this implies a limit of $g^{-1} > 1.32{\times}10^{11}$ GeV. However, there are considerable uncertainties involved in the calculation, principally in the details of the galactic magnetic field, and the energy dependence of the detector response. If we assume that there is an uncertainty of a factor of three in our calculated fluence, then our limit is weakened to $g^{-1} > 1.0{\times}10^{11}$ GeV. Note that since the photon flux is proportional to g^4, the g limit is rather insensitive to small errors in the flux or detection calculation.

V. DISCUSSION AND SUMMARY

We have found that the absence of excess γ-rays from SN 1987A limits the photon coupling of a nearly massless pseudoscalar $g^{-1} > 1{\times}10^{11}$ GeV. This limit is significantly more restrictive than $g^{-1} > 1.7{\times}10^{10}$ GeV which is found from the classic energy-loss argument applied to horizontal-branch stars [4,5]. However, the latter argument is valid for pseudoscalar masses of up to about 10 keV and thus covers the important case of axions. Of course, for axions even more restrictive limits obtain from their coupling to nucleons on the basis of the energy-loss argument applied to

SN 1987A. Our present result is primarily useful for hypothetical massless Goldstone bosons which do not exhibit significant couplings to "normal" fermions such as electrons or nucleons. If they had such couplings one would typically expect that these couplings yield more restrictive limits on the underlying scale of symmetry breaking. Ignoring such couplings also justifies that we focused on the Primakoff effect to estimate the mean free path in the SN core. In principle, of course, arbitrary pseudoscalars could be trapped by interactions with nucleons or electrons.

In a previous paper [6], one of us (E.C.) considered what limit had been set or could be set by looking for γ-rays from stars, particularly the nearby supergiant α-Ori (Betelgeuse). A limit of $g^{-1} > 4\times10^{10}$ GeV was set by reexamining old data, and it was pointed out that this limit could be improved to the level of 1×10^{11} GeV if a dedicated observation were made. We have achieved this goal with the existing SN 1987A data.

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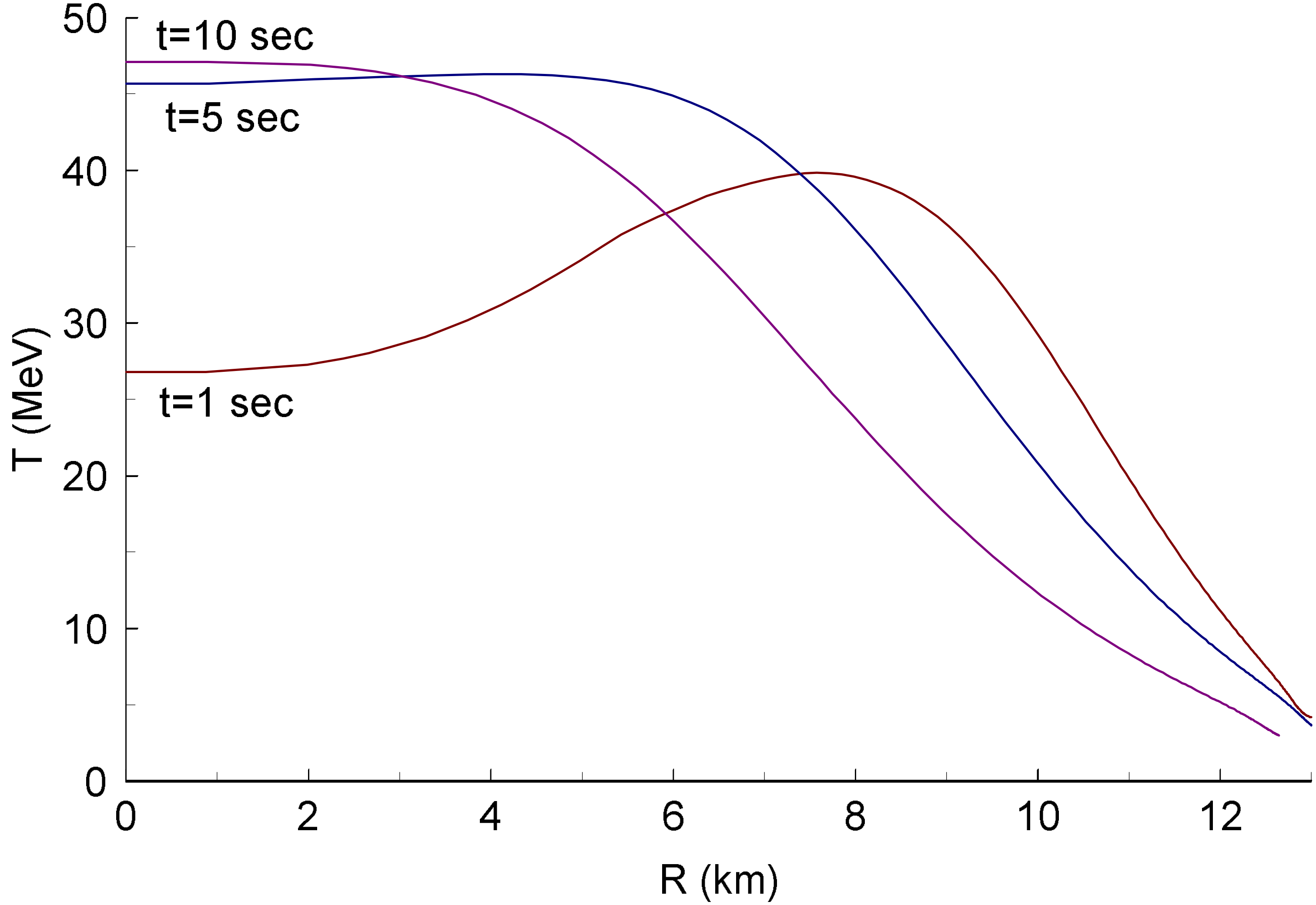
Figure Captions

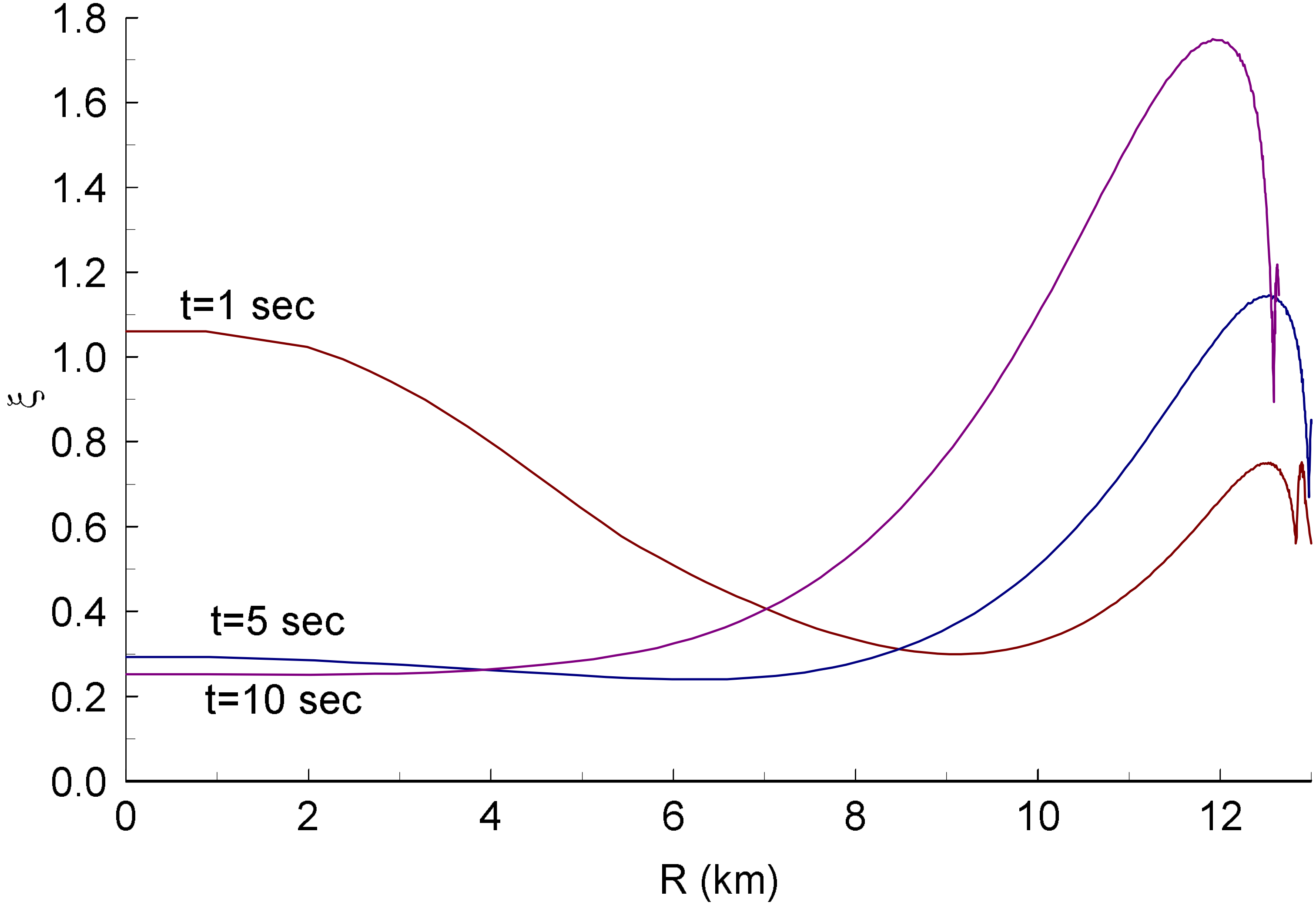
Fig. 1. The temperature T (1a) and the parameter ξ (1b) as functions of radius for times t=1, 5, and 10 seconds, based on the model S2BH_0 of Keil, Janka and Raffelt [9].

Fig. 2. The parameter T/E_{F} (proton Fermi energy E_{F}) as a function of radius r for t=1, 5, and 10 seconds after core bounce, based on the model S2BH_0 of Keil, Janka and Raffelt [9].

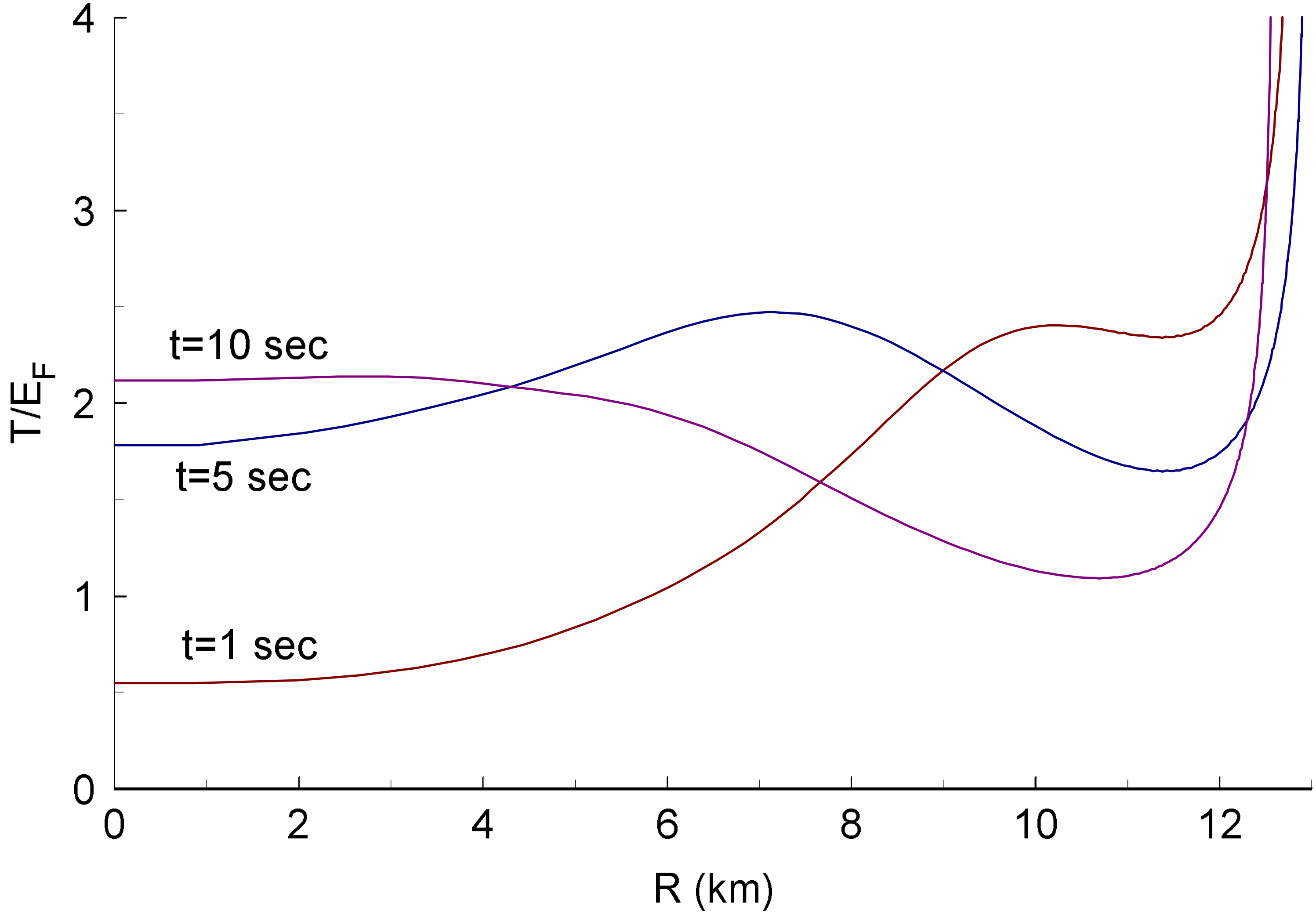
Fig. 3. The number of pseudoscalars produced (left scale) and resulting γ-ray photon flux at the Earth (right scale) for a coupling $g^{-1} = 10^{10}$GeV for times t=1, 5, and 10 seconds.



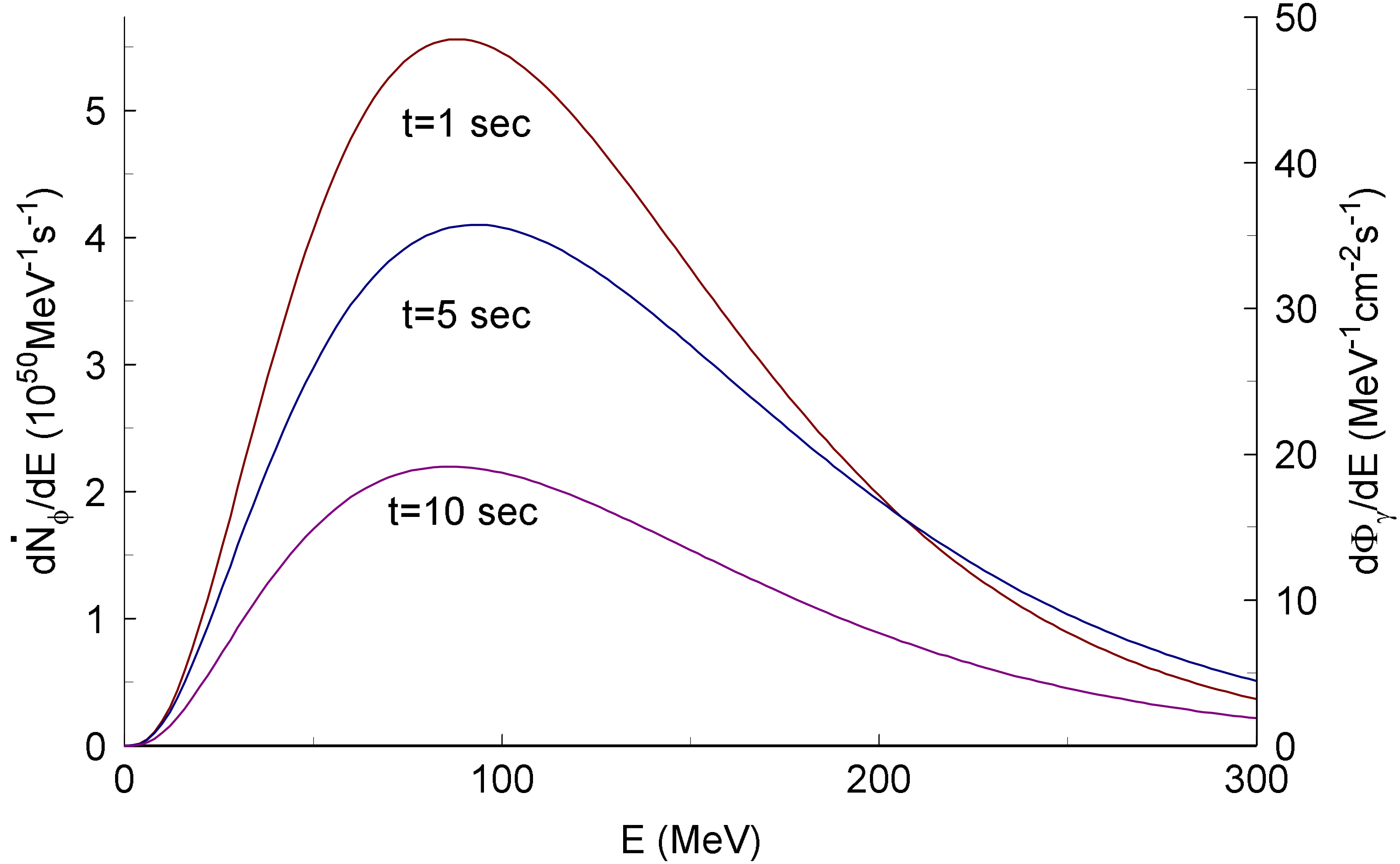
t=10 sec
t=5 sec
t=1 sec
T (MeV)
R (km)
0
10
20
30
40
50
0
2
4
6
8
10
12



1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
ξ
t=1 sec
t=5 sec
t=10 sec
0
2
4
6
8
10
12
R (km)



4
3
2
1
0
T/E_F
t=10 sec
t=5 sec
t=1 sec
0
2
4
6
8
10
12
R (km)



t=1 sec
t=5 sec
t=10 sec
$d\dot{N}_\phi/dE$ (10^{50}MeV^{-1}s^{-1})
$d\Phi_\gamma/dE$ (MeV^{-1}cm^{-2}s^{-1})
E (MeV)
0
100
200
300
0
1
2
3
4
5
0
10
20
30
40
50